Appendix R

Correlation of two thermal models

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Abstract

Reduced thermal models are often required in the design phase of projects. Reduced models have the advantage that they provide a reasonable level of accuracy while maintaining short calculation times. It is common to first build a detailed model, which is then reduced in the same software package. Grouping of nodes and thermal properties requires a lot of physical insight and can be a tedious job.
This presentation will offer a different approach with the same advantages, but without the tedious node grouping in the reduction step. An analytical model for the thermal analysis of wiring is correlated with a more accurate numerical model. By this correlation, the level of accuracy of the analytical model is increased, while maintaining short calculation times. The model has been developed for aircraft applications, but can be used for aerospace applications as well. After a short introduction in the model and its applications, the presentation will mainly focus on the different steps in the correlation process.

Correlation of two thermal models

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Dedicated to innovation in aerospace

open engineering

Outline of the presentation

- Common way of model reduction
- Description of the models
- Correlation of the two models
- Using RMS as measure
- Fine-tuning of correlation using test results
- Conclusions and recommendations

Common way of model reduction

- Select approach, e.g. nodal model
- Build detailed model in ESATAN
  - If detailed FEM model is available, FEM model can be converted to ESATAN model
  - Depending on application the number of nodes can vary from a couple of dozens to over 1,000 nodes
  - For each node, the thermal properties have to be added
- Group nodes
  - Limited number of nodes allowed
  - Select nodes with similar properties and group them (TEDIOUS!)
  - Combine the thermal properties of all nodes in a group

Common way of model reduction

Objective:
Use as much of the information from the detailed model as possible in the reduced model without increasing the calculation time of the reduced model

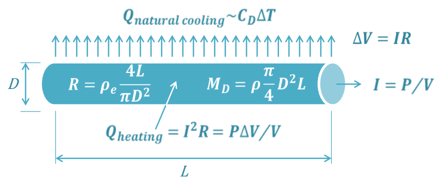
Reduced model is often used integrated in a larger model

Advantages reduced model:
- Fast results
- Decent level of accuracy despite limited level of detail

These advantages can also be obtained by correlation of two models
- Model 1: analytical model ('reduced' model)
- Model 2: numerical model ('detailed' model)

Description of the models

Application:
Thermal analysis of wiring bundle designs (of aircraft, but the model can also be used for (aero)space applications)



Objective:
Investigate weight reductions and improved safety

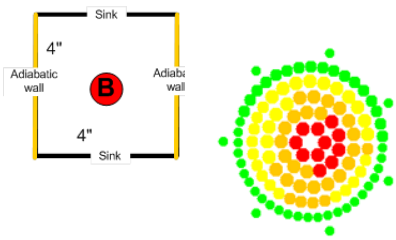
Description of the models

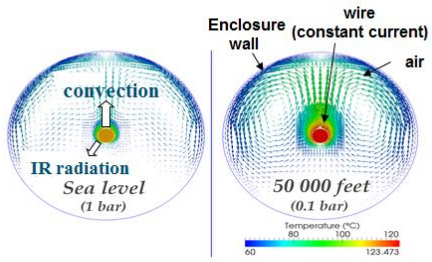
TDM – 'reduced' model

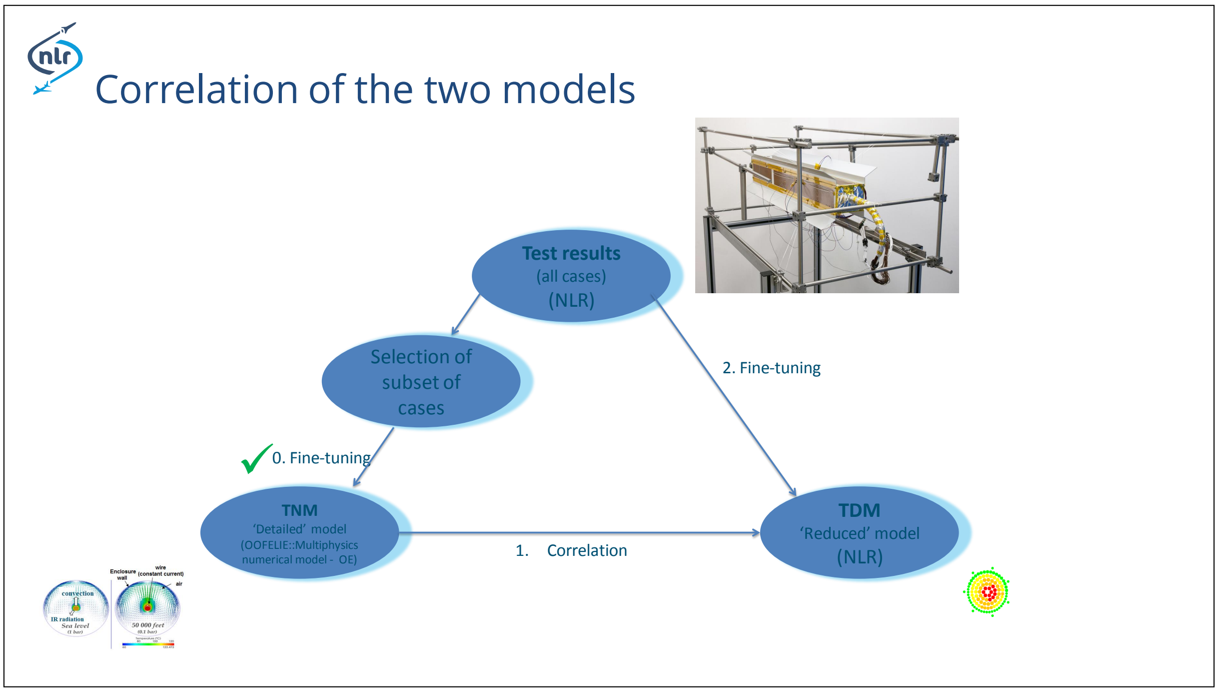
- Low level of detail
- Java model using a matrix solver (steady state)
- Network model
- Heat transfer calculated using analytical functions
- Typical calculation time per case: ~ 1 sec.

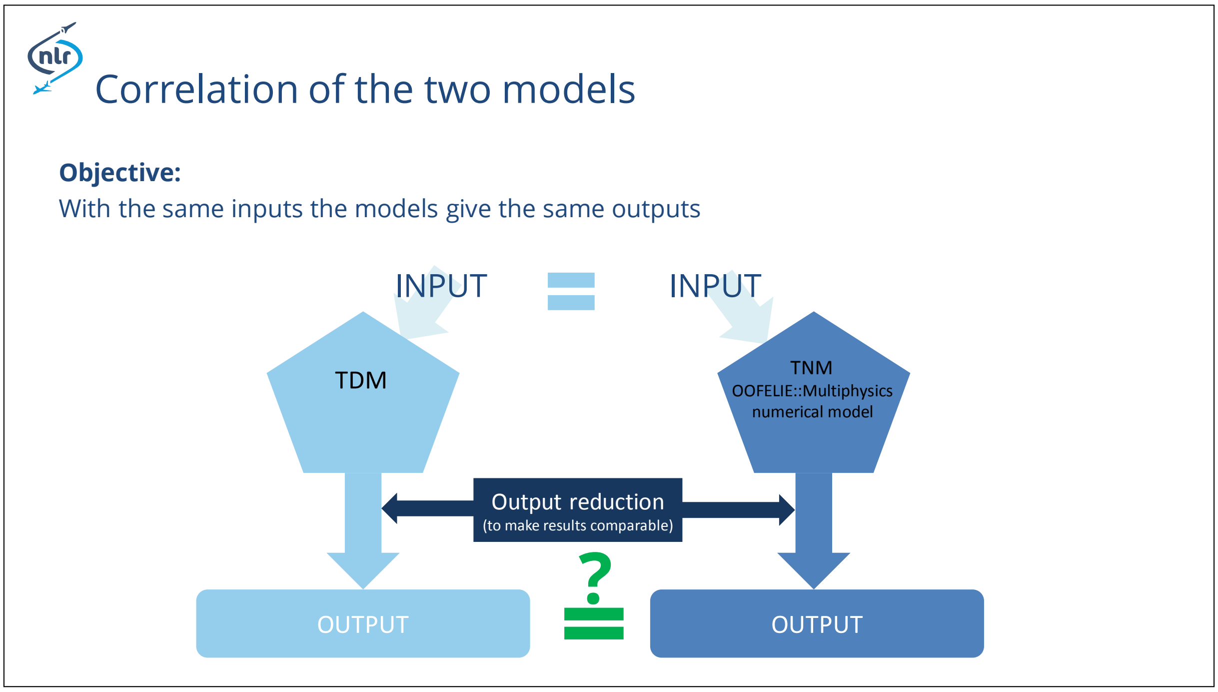
OOFELIE::Multiphysics numerical model
(Open Engineering)

- High level of detail
- Fine grid
- 3D model
- Complex, detailed calculations for heat transfer
- Typical calculation time per case: ~ 1 hour






Correlation of the two models
Test results
(all cases)
(NLR)
Selection of subset of cases
2. Fine-tuning
0. Fine-tuning
TNM
'Detailed' model
(OOFELIE::Multiphysics numerical model - OE)
1. Correlation
TDM
'Reduced' model
(NLR)


Correlation of the two models
Objective:
With the same inputs the models give the same outputs
INPUT
INPUT
TDM
TNM
OOFELIE::Multiphysics numerical model
Output reduction
(to make results comparable)
OUTPUT
OUTPUT

Correlation of the two models

Assumption:
For the same set of inputs both models give the same output if each coupling C (conductive, radiative and convective) from *i* to *j* is the same ∀ *i,j*

Approach:
Find function *f(x)* such that $f(x) * C_{ij\_TDM} = C_{ij\_TNM}$

Conditions:
- Function *f(x)* is different for conductive, radiative and convective couplings and for different combinations of *i* and *j*
- Only one dependency is allowed in the function *f(x)*, i.e., *x* can be e.g. pressure or power

Correlation of the two models

Question: How can C_{ij_TDM} and C_{ij_TNM} be found?

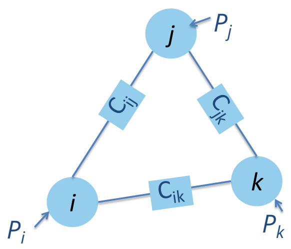
Answer:
Sensitivity analysis

Example: 3 nodes, only conduction

$$P_i = C_{ij} * (T_i - T_j) + C_{ik} * (T_i - T_k)$$

$$T_i = \frac{1}{C_{ij}+C_{ik}} P_i + \frac{C_{ij}}{C_{ij}+C_{ik}} T_j + \frac{C_{ik}}{C_{ij}+C_{ik}} T_k$$

$$C_{ij} = \frac{C_{ij}+C_{ik}}{1} * \frac{C_{ij}}{C_{ij}+C_{ik}} = \left(\frac{\partial T_i}{\partial P_i}\right)^{-1} \left(\frac{\partial T_i}{\partial T_j}\right)$$



Sensitivity analysis: $$\frac{\partial T_i}{\partial T_j} \cong \frac{T_i(T_j = T_0 + \Delta T) - T_i(T_j = T_0)}{\Delta T}$$

Correlation of the two models

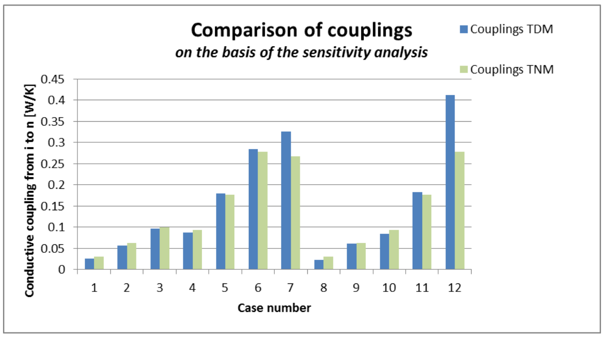
$f(x)*C_{ij\_TDM} = C_{ij\_TNM}$

Use the sensitivity to find all C_{ij_TDM} and C_{ij_TNM}
Assess what *x* in *f(x)* could be:

General:	Power [W]	Pressure [bar]	T1 [°C]	T2 [°C]	T3 [°C]	T4 [°C]
Specific to this model:	Power [W]	Pressure [bar]	T_air [°C]	T_bndl [°C]	T_sink [°C]	T_wall [°C]
C(i,j) (convective)	y	y	y	n	n	n
C(i,k) (convective)	y	y	y	n	n	n
C(i,j) (radiative)	y	n	n	n	y	n
C(i,k) (radiative)	y	n	n	n	y	n
C(i,j) (conductive)	y	n	n	y	n	n
C(i,k) (conductive)	y	n	n	y	n	n
C(m,j) (convective)	y	y	y	n	n	n
C(m,k) (convective)	y	y	y	n	n	n
C(m,j) (radiative)	y	n	n	n	n	y
C(m,k) (radiative)	y	n	n	n	n	y

Correlation of the two models

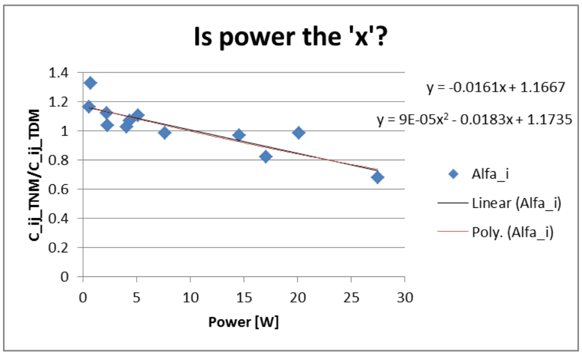
To find the function *f(x)* such that $f(x)*C_{ij\_TDM} = C_{ij\_TNM}$ a comparison of the couplings is needed

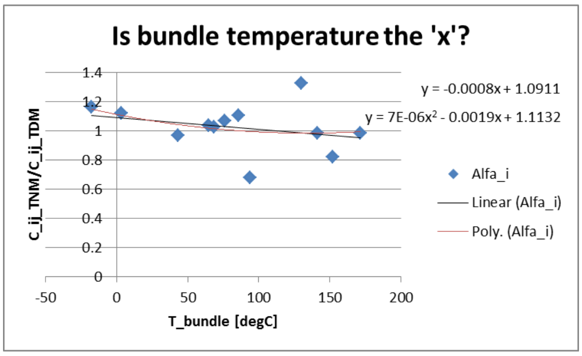


Correlation of the two models

	Power [W]	Pressure [bar]	T_air [degC]	T_bndl [degC]	T_sink [degC]	T_wall [degC]
C(i,j) (conductive)	y	n	n	y	[illegible]	n

If $f(x) * C_{ij\_TDM} = C_{ij\_TNM}$, then $f(x) = C_{ij\_TNM} / C_{ij\_TDM}$





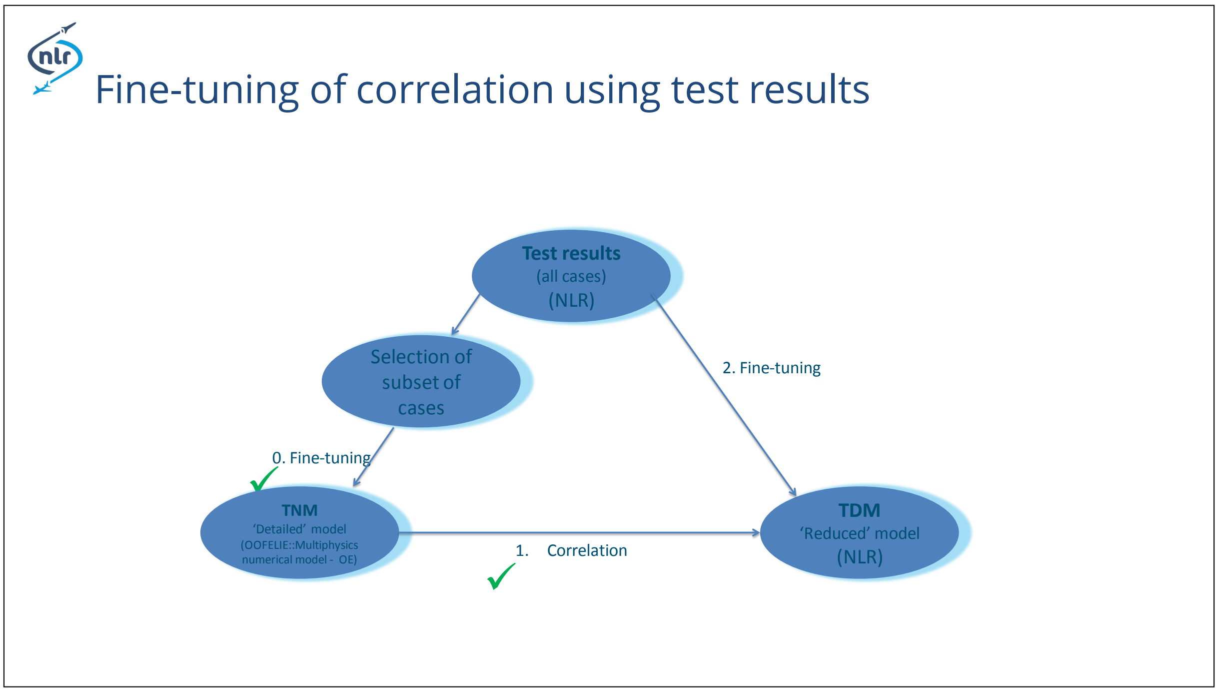
Using RMS as a measure

- Implement all correlation functions (one for each coupling) in the TDM
- The root mean square can be used as a measure for how much the TDM has improved:

$$RMS = \sqrt{\frac{\sum_{i=1}^{N} (T_{TDM\_i} - T_{TNM_i})^2}{N}}$$

- Calculate RMS using the complete subset of cases
- Result:

Correlation step	RMS value
Uncorrelated TDM	10.51
Correlated TDM	16.38
Fine-tuned, correlated TDM	7.69


Fine-tuning of correlation using test results
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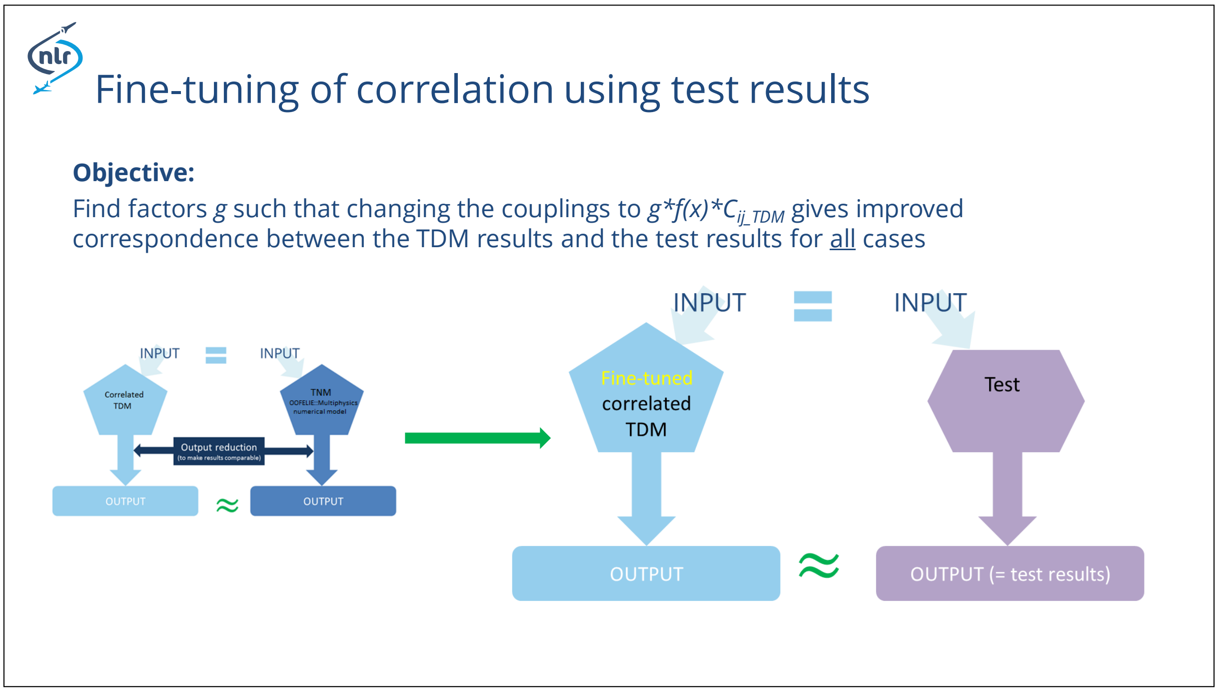
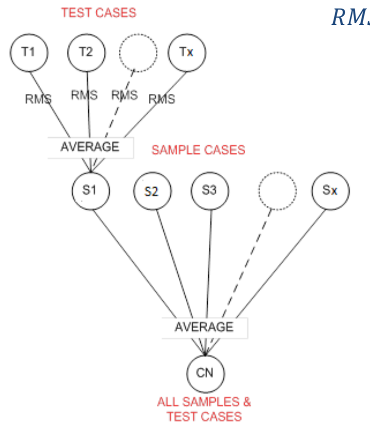

Fine-tuning of correlation using test results
Objective:
Find factors g such that changing the couplings to g*f(x)*C_ij_TDM gives improved correspondence between the TDM results and the test results for all cases
INPUT
INPUT
Correlated TDM
TNM
OOFELIE::Multiphysics numerical model
Output reduction
(to make results comparable)
OUTPUT
OUTPUT
INPUT
INPUT
Fine-tuned correlated TDM
Test
OUTPUT
OUTPUT (= test results)

Fine-tuning of correlation using test results

Measure to determine improvement of correlation:

Correlation Number

$$RMS = \sqrt{\frac{\sum_{i=1}^{N}(T_{TDM\_i} - T_{test\_i})^2}{N}}$$



Fine-tuning of correlation using test results

Results:

Fine-tuning step	CN value	Fine-tuning improvements
At start (after finishing TNM correlation)	13.67	
After ~50 iterations	5.89	• Fine-tuning inputs • Slightly scale some correlation functions • Apply some additional minor changes

Conclusions

- **Correlation of two models could be an alternative approach for model reduction, while tedious grouping and reducing step can be avoided**
- **Sensitivity analyses are used to estimate heat transfer couplings**
- **The number of investigated correlation functions has been reduced by a priori assessment of physical dependencies**
- **Use of the sensitivity analysis leads to optimal correlation functions between the models. However, manual fine-tuning is still required.**
- **Correlated TDM gives results that are much better (±10°C) in line with the test results than previous TDM (±15°C)**

Recommendations

- **More research is required to generalize the methodology used**
- **Automation of sensitivity analysis and calculation of correlation functions could be a valuable tool for model comparison without a priori physical understanding of the system**